

# New results of the Berliner relativistic quark model<sup>§</sup> \*

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## Abstract

It is pointed out that the recently measured left-right asymmetries in inclusive pion and lambda hyperon production processes are in very good agreement with the relativistic quark model, proposed some time ago. Further predictions based on this model for hyperon productions, for lepton pair productions and for W/Z-boson productions are also presented.

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# 1 Introduction

Inclusive pion, and  $\eta$ -meson production experiments using transversely polarized 200  $GeV/c$  proton or antiproton projectiles and unpolarized targets has shown that the left-right asymmetries are not only very large in the fragmentation region of the polarized hadrons but also that they depend on the flavor content of the polarized colliding objects and on that of the produced particles [1, 2]. Recently also the left-right asymmetry in single-spin  $\Lambda$  hyperon production in proton-proton collisions has been measured [3]. The data shows that the asymmetry is zero for small  $x_F$  ( $x_F < 0.2$ ), than slightly positive in the region  $0.2 < x_F < 0.5$  (although it is compatible with zero within the error bars in this region) and above  $x_F = 0.5$  it is large and negative. An interesting feature of the observed asymmetry is that it becomes significant for much larger  $x_F$  than that for pion production.

These asymmetries are expected to vanish in the usual leading twist pQCD-based hard-scattering model [4], suggesting that soft dynamics should be important in understanding the experimental data. Several attempts have been made in trying to include higher twist effects in the framework of the hard-scattering model [5]. In this talk I want to focus on a somewhat different approach which has been proposed by the Berliner group and is sometimes called the Berliner relativistic quark model. These phenomenological model has been successfully used in describing the existing experimental data and predicting the outcome of some single-spin experiments long before the corresponding data were available [6-9]. In the following I wish to point out that one can also understand the  $\Lambda$  hyperon data in terms of the proposed model and present predictions for other hyperon production processes [10]. It has been emphasized that as a consequence of the model not only meson and hyperon production processes but also the corresponding lepton pair and W/Z-boson production should show significant left-right asymmetries and by measuring these asymmetries one can test the proposed model [8, 9]. Thus it is crucial to have definite predictions for these processes. In this talk I discuss the production of Drell-Yan pairs using pion beam and different polarized targets and the asymmetries involved in single-spin inclusive W/Z-boson production in proton-proton and antiproton-proton collisions. The material presented here has been obtained in collaboration with Prof. Meng and Dr. Liang.

## 2 The physical picture

Let us summarize first briefly the key points of the model [6-9].

(i) Valence quarks in hadron are treated as relativistic dirac particles in an effective confining potential. It can be readily shown that orbital motion is always involved. Furthermore the direction of the orbital motion is determined uniquely by the polarization of the valence-quark.

(ii) Valence quarks in a polarized hadron are polarized either in the same or in the opposite direction as the hadron. This is determined by the wave function of the hadron. For proton we have that 5/3 of the u-quarks are polarized in the same and 1/3 of them in the opposite direction as the polarized hadron. For d-quarks we have 1/3 and 2/3 respectively.

(iii) In the fragmentation regions of the high-energy hadron-hadron collisions a significant part of the mesons/hyperons are products of direct-formation processes between the valence-quarks of the one hadron with suitable sea-quarks of the other hadron.

(iv) Because of the fact, that hadrons are extended objects and their constituents interact with each other we expect that there exists a surface effect, i.e. only those mesons, hyperons which are produced on the front surface of the polarized hadron, retain information about the polarization.

In order to compare the proposed picture with the recent experiments, let us recall how the left-right asymmetry is defined for the reaction  $p(\uparrow) + p(0) \rightarrow (pp) + X$  where  $pp$  stands for the produced particle, which is either a meson or a baryon or a lepton pair.

$$A_N(x_F, Q|s) \equiv \frac{N(x_F, Q|s, \uparrow) - N(x_F, Q|s, \downarrow)}{N(x_F, Q|s, \uparrow) + N(x_F, Q|s, \downarrow)} \quad (1)$$

where

$$N(x_F, Q|s, \uparrow / \downarrow) \equiv \frac{1}{\sigma_{in}} \int_D d^2 p_{\perp} \frac{d\sigma}{dx_F dp_{\perp}^2(x_F, \vec{p}_{\perp}, Q|s)} (\uparrow / \downarrow) \quad (2)$$

is the normalized number density of the observed particle in a given kinematical region D when the projectile is polarized upwards ( $\uparrow$ ) /polarized downwards ( $\downarrow$ ).  $\sigma_{in}$  is the total inelastic cross section,  $x_F \equiv 2p_{||}/\sqrt{s}$ , where  $p_{||}$  is the longitudinal component of the momentum of the produced particle and  $s$  is the total c.m. energy squared of the incoming hadrons,  $Q$  is the invariant mass of the produced particle. According to the proposed picture  $\Delta N(x_F, Q|s) \equiv N(x_F, Q|s, \uparrow) - N(x_F, Q|s, \downarrow)$  is proportional to  $\Delta D(x_F, Q|s) \equiv D(x_F, Q|s, +) - D(x_F, Q|s, -)$  that is

$$\Delta N(x_F, Q|s) = C \Delta D(x_F, Q|s) \quad (3)$$

where  $D(x_F, Q|s, \pm)$  is the number density of the produced particles formed through annihilation of valence quarks polarized in the same/opposite direction as the projectile.  $D(x_F, Q|s, \pm)$  is a convolution of three different functions. The first one,  $q_v^{\pm}(x^P)$ , is the number density of the valence quarks  $q_v$

polarized in the same/opposite direction as the transversely polarized hadron,  $q_s(x^T)$  is the number density of the sea-quarks in the unpolarized target and  $K(x^P, q_v, x^T, \bar{q}_s, x_F, Q|s)$  is the probability for the direct formation. For baryon production it is understood that either  $q_v^\pm(x^P)$  or  $q_s(x^T)$  stands for a diquark. The constant  $C$  describes the intensity of the surface effect.

For meson or baryon production we have

$$D(x_F, M|s, \pm) = \kappa_M q_v^\pm(x^P) \bar{q}_s(x^T) \quad (4)$$

where  $x^P$  and  $x^T$  are determined by momentum conservation  $x^P \approx x_F$  and  $x^T \approx x_0/x_F$  with  $x_0 = m_M^2/s$  ( $m_M$  is the mass of the produced particle). The denominator is nothing else but  $2N(x_F, M|s)$  the number density of observed particles in the corresponding unpolarized reaction and it can be written as the sum of two terms [7, 8] :

$$N(x_F, M|s) = N_0(x_F, M|s) + D(x_F, M|s) \quad (5)$$

Here  $D(x_F, M|s) = D(x_F, M|s, +) + D(x_F, M|s, -)$  stands for the direct formation and is meant as the sum over all possible direct formation processes,  $D(x_F, M|s) = \sum_i D_i(x_F, M|s)$ ,  $N_0(x_F, M|s)$  stands for other contributions than direct formation and can be extracted from the existing data. With this we have for meson production:

$$A_N(x_F, M|s) = C \kappa_M \frac{\Delta q_v(x^P) \bar{q}_s(x^T)}{2[N_0(x_F, \pi|s) + D(x_F, \pi|s)]}, \quad (6)$$

For lepton pair production we have

$$D(x_F, Q|s, \pm) = \sum_q e_q^2 q_V^\pm(x^P) \bar{q}_s(x^T) \quad (7)$$

where  $q = q_v = q_s$  is the flavor content of the quarks and  $x^{P/T}$  are given by  $x^{P/T} = [\pm x_F + \sqrt{x_F^2 + (4Q^2)/s}]/2$ .

In carrying out these calculations, it is useful to note the following: By integrating  $q_v^\pm(x)$  over  $x$ , we obtain the average number of the valence quarks  $q_v$  polarized in the same/opposite direction as the proton. That is,  $\Delta q_v(x) \equiv q_v^+(x) - q_v^-(x)$  satisfies the following constraints:

$$\int dx \Delta u_v(x) = 4/3, \quad \int dx \Delta d_v(x) = -1/3 \quad (8)$$

Since the  $q_v^\pm(x)$ 's have not yet been measured, in order to estimate the main features of the asymmetries we use the following rough estimate:

$$\Delta u_v(x) = (2/3)u_v(x), \quad \Delta d_v(x) = -(1/3)d_v(x), \quad (9)$$

### 3 Left-right asymmetry in inclusive hyperon production

In inclusive hyperon production we have three different contributions to the cross section:

- (a) Diquarks of the projectile form hyperons with sea quarks of the target.
- (b) Valence quarks of the projectile form hyperons with sea diquarks of the target.
- (c) and finally we have the non direct formation processes in the central rapidity region.

It is clear that process (c) will mainly contribute in the central rapidity region. While the processes (a) and (b) will contribute mainly in the projectile fragmentation region and here process (a) will contribute at higher  $x_F$  than process (b) because valence *diquarks* carry in general a larger fraction of momentum than valence *quarks*.

Let us discuss  $\Lambda$  production first. We have to determine the different contributions to the number density of the produced  $\Lambda$  hyperon in unpolarized proton-proton collisions  $N(x_F, \Lambda|s)$  :

$$N(x_F, \Lambda|s) = N_0(x_F, \Lambda|s) + D^d(x_F, \Lambda|s) + D^v(x_F, \Lambda|s) \quad (10)$$

$D^d(x_F, \Lambda|s)$  is the contribution from valence diquark – sea quark annihilation and is given by:

$$D^d(x_F, \Lambda|s) = \kappa_\Lambda^d (ud)_v (x^P) s_s (x^T) \quad (11)$$

$D^v(x_F, \Lambda|s)$  is the contribution for valence quark – sea diquark formation:

$$D^v(x_F, \Lambda|s) = \kappa_\Lambda^v \{u_v(x^P)(ds)_s(x^T) + d_v(x^P)(us)_s(x^T)\} \quad (12)$$

where for the sea diquark distribution  $(qq)_s$  with  $q = u, d, s$  we use a convolution of two sea quark distributions. For the valence diquark distribution  $(ud)_v$  we use the parametrization of [12]. The two constants  $\kappa_\Lambda^d$  and  $\kappa_\Lambda^v$  and the contribution coming from the non direct formation processes are to be determined by fits to the data. For the functional form of the non direct formation we choose:  $300(1 - x_F)^2 e^{-3x_F^3}$ . In Fig.2 a comparison is made with the data of Ref. [11]. The data can be reproduced very well, suggesting that hyperons are indeed produced by direct formation Eq.(11) and Eq.(12) in the fragmentation region.

In order to discuss the asymmetry in the process  $p(\uparrow) + p(0) \rightarrow \Lambda + X$  we note that only valence quarks of the polarized projectile contribute to the asymmetry and we have in detail the following behavior for the different terms:  $u_v + (ds)_s \rightarrow \Lambda$  contributes positively,  $d_v + (us)_s \rightarrow \Lambda$  negatively and the process  $(ud)_v + s_s \rightarrow \Lambda$  contributes also negatively to the asymmetry. The signs of the first two contributions are due to Eq.(8). In order to understand the sign of the last contribution, we note the following : This direct formation process should be predominantly

accompanied by the production of a meson, directly formed through fusion of the  $u$ -valence quark of the projectile with a suitable anti-sea-quark of the target. This meson should have a large probability to go left. Thus according to momentum conservation, the  $\Lambda$  produced through this process should go right. This implies that this formation process contributes negatively to the asymmetry. Thus these contribution is opposite in sign to that of the associatively produced meson and is proportional to  $-r_u(x) \equiv -\Delta u_v(x)/u_v(x)$ , where  $x$  is the fractional momentum of the  $u_v$  valence quark. Thus we have for the asymmetry:

$$A_N(x_F, \Lambda|s) = \frac{C \kappa_\Lambda^v [\Delta u_v(x^P) + \Delta d_v(x^P)] (qq)_s(x^T) - \kappa_\Lambda^d r_u(x) (ud)_v(x^P) s_s(x^T)}{2[N_0(x_F, \Lambda|s) + D^d(x_F, \Lambda|s) + D^v(x_F, \Lambda|s)]} \quad (13)$$

Since the non direct formation processes do not contribute to the asymmetry, it will be zero in the central rapidity region  $x_F < 0.2$ . In the region where the first two processes already contribute  $0.3 < x_F < 0.5$  the asymmetry will be slightly positive because we have  $(\Delta u_v(x^P) + \Delta d_v(x^P))(qq)_s(x^T) = (\frac{2}{3}u_v(x^P) - \frac{1}{3}d_v(x^P))(qq)_s(x^T)$ . Finally in the large  $x_F$  region the contribution  $(ud)_v + s_s \rightarrow \Lambda$  dominates and the asymmetry will be large and negative. If we use the ansatz of Eq.(10), we have for  $r_u(x) = 2/3$ . In Fig.3 a comparison is made with the data using the constants for  $\kappa_\Lambda^i$  determined from the unpolarized cross section.

Since for other hyperons the unpolarized differential cross sections are not yet well known we can only make qualitative predictions for these asymmetries. For  $\Sigma^- = dds$  the only contribution in the projectile fragmentation region comes from  $d_v + (ds)_s \rightarrow \Sigma^-$  i.e. the asymmetry will be negative. For  $\Sigma^+ = uus$  we have the contribution  $u_v + (us)_s \rightarrow \Sigma^+$  which is positive and we have also contribution from  $(uu)_v + s_s \rightarrow \Sigma^+$  which contributes positively to the asymmetry. Thus  $\Sigma^+$  behaves like  $\pi^+$  and  $\Sigma^-$  behaves like  $\pi^-$ . Although  $\Sigma^0 = uds$  has the same flavor content as  $\Lambda$ , there is the following difference: While the  $ud$ -valence-diquark in  $\Lambda$  is in the state with the sum of their total angular momenta  $j_{ud} = 0$ , the  $ud$ -valence-diquark in  $\Sigma^0$  is in a  $j_{ud} = 1$  state. We note that the proton wave function [7] can be written in the following way,

$$|p(\uparrow)\rangle = \frac{1}{2\sqrt{3}} \left\{ 3u(\uparrow) \cdot \frac{1}{\sqrt{2}} [u(\uparrow)d(\downarrow) - u(\downarrow)d(\uparrow)] + u(\uparrow) \cdot \frac{1}{\sqrt{2}} [u(\uparrow)d(\downarrow) + u(\downarrow)d(\uparrow)] - \sqrt{2}u(\downarrow)u(\uparrow)d(\uparrow) \right\}, \quad (14)$$

where  $(\uparrow)$  and  $(\downarrow)$  denote the  $z$ -component of the total angular momentum of the corresponding valence quark which is  $j_z = +1/2$  or  $j_z = -1/2$  respectively. We see clearly that, if the  $ud$ -diquark is in a  $j_{ud} = 1$ -state, the other  $u$ -valence-quark is either polarized upward or downward, with relative probabilities 1 : 2. So if  $\Sigma^0$  is produced through the same kind of direct formation process as shown in (a), the associatively produced meson should have a large probability to go right.

Hence, we expect that  $A_N(x_F, \Sigma^0|s)$  behaves differently from  $A_N(x_F, \Lambda|s)$  does in the large  $x_F$  region ( $x_F > 0.6$ , say). In contrast to  $A_N(x_F, \Lambda|s)$ ,  $A_N(x_F, \Sigma^0|s)$  is positive in sign in this region. This implies also that there is no change of sign in  $A_N(x_F, \Sigma^0|s)$  as a function of  $x_F$ .

For  $\Xi^- = dss$  the contributions are  $d_v + (ss)_s \rightarrow \Xi^-$ , so that the asymmetry is negative while the asymmetry is positive for  $\Xi^0 = uss$  due to  $u_v + (ss)_s \rightarrow \Xi^0$ . Furthermore anti- $\Lambda$  should not show any asymmetries since only sea-quarks or sea-diquarks of the polarized projectile contribute. However for antiproton beam anti- $\Lambda$  behaves in the same way as  $\Lambda$  for proton beam, and  $\Lambda$  in the same way as anti- $\Lambda$  for proton beams (i.e. no asymmetry). These features are summarized in the following table for proton-proton collision:

hyperon	$\Sigma^-$	$\Sigma^0$	$\Sigma^+$	$\Xi^-$	$\Xi^0$	$\Lambda$	<i>anti</i> - $\Lambda$
asymmetry	neg.	pos.	pos.	neg.	pos.	neg.	0.

## 4 Left-right asymmetry in other processes

Now we come to the production of Drell-Yan pairs using pion beams and different polarized targets:  $\pi^\pm + p(\uparrow), n(\uparrow), D(\uparrow) \rightarrow \bar{l}l + X$ . Since here non-direct formation processes do not contribute and valence-valence annihilation plays the dominating role we expect that the asymmetries are large not only in the fragmentation region of the polarized particles (in contrast to meson/hyperon production). Let us discuss first the difference between  $\pi^+$  and  $\pi^-$  using polarized proton target. Since the valence-valence contribution  $\bar{u}_v^{\pi^-} - u_v$  plays the dominating role in the whole kinematic region for  $\pi^- + p(\uparrow) \rightarrow \bar{l}l + X$  this asymmetry is expected to be negative and its magnitude be large. In  $\pi^+ + p(\uparrow) \rightarrow \bar{l}l + X$  the valence contribution is due to  $\bar{d}_v^{\pi^+} - d_v$  which is of the same order of magnitude as the  $\bar{u}_s^{\pi^+} - u_v$ -contribution or even smaller in the target fragmentation region. We expect that the corresponding asymmetry is negative in the target fragmentation region and positive in the projectile fragmentation region.

If one uses the same beam, say  $\pi^-$ , and different projectiles, one expects also considerable differences. We compare  $\pi^- + p(\uparrow) \rightarrow \bar{l}l + X$  with  $\pi^- + n(\uparrow) \rightarrow \bar{l}l + X$ . In both reactions the asymmetries are due to  $\bar{u}_v^{\pi^-} - u_v$ . But because of isospin symmetry  $\bar{u}_v^{\pi^-} - u_v$  contributes in  $\pi^- + p(\uparrow) \rightarrow \bar{l}l + X$  negatively to  $A_N$  (note that now the target, not the projectile, is polarized therefore the minus sign) and it contributes positively in  $\pi^- + n(\uparrow) \rightarrow \bar{l}l + X$ . In Fig.3 we see that the asymmetry depends very much on what kind of target we have. A similar discussion can be made for  $\pi^+$  using different polarized projectiles. The results should not be repeated here, they are published in Ref. [8].

According to the proposed picture W/Z-boson production processes in single-spin experiments should also show left-right asymmetries. Since the largest contributions come from the annihilation of anti-valence quarks of the polarized

antiproton beam and valence-quarks of the unpolarized proton target in the reaction  $\bar{p}(\uparrow) + p(0) \rightarrow W/Z + X$  we only need to take them into account. Here we see that the asymmetry for  $W^+$  is negative due to  $\bar{d}_v^p - u_V^p$  and that for  $W^-$  is positive due to  $\bar{u}_v^p - d_V^p$  and that for  $Z$  is positive but smaller than that for  $W^-$ .

In the case of  $p(\uparrow) + p(0) \rightarrow W/Z + X$  the main contributions to the asymmetries come from the annihilation of valence-quarks of the polarized projectile and anti-sea quarks of the unpolarized target. Here we have positive asymmetry for  $W^+$  due to  $u_v^p - \bar{d}_s^p$  and negative asymmetry for  $W^-$  due to  $d_v^p - \bar{u}_s^p$  annihilation.  $W^+$  and  $W^-$  change their role in proton and antiproton induced reactions. The sign for the asymmetry of the  $Z$ -boson remains the same.

## 5 Conclusions

It is pointed out that not only the asymmetries observed in inclusive meson production processes but also the recent experimental data for  $\Lambda$  hyperon production are in good agreement with the Berliner relativistic quark model. Further predictions for other hyperon productions, Drell-Yan pair and  $W/Z$ -boson productions have been presented.

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## Figure captions

Fig.1. The differential cross section  $Ed\sigma/dp^3$   $p(0) + p(0) \rightarrow \Lambda + X$  at ISR-energy  $\sqrt{s} = 62.3$  GeV/c and for  $p_{\perp} = 0.65$  GeV/c [11]. The different contributions : valence diquark – sea quark, valence quark – sea diquark and non-direct formation are plotted as dashed-dotted, dotted and dashed lines respectively. The solid line is the sum of all contributions. The spin averaged distribution are from Ref. [13], the diquark distributions are from Ref.[12].

Fig.2. The left-right asymmetry  $A_N$  for  $p(\uparrow) + p(0) \rightarrow \Lambda + X$ . The data at 200 GeV/c are from Ref. [15] and the low energy data are from Ref. [3]. The constant  $C$  which parametrizes the surface effect is chosen to be 0.6 as in [8].

Fig.3. The left-right asymmetry  $A_N$  for lepton pair production using 70 GeV/c  $\pi^-$  beam and different polarized targets. The spin averaged distribution are from Ref. [13] for proton and from Ref. [14] for pion.

Fig.4. The left-right asymmetry  $A_N$  for W/Z-boson production,  $p(\uparrow) + p(0) \rightarrow W^{\pm}/Z + X$  at  $\sqrt{s} = 500$  GeV/c. The same parametrization for the quark-distribution functions has been used as in Fig.3.

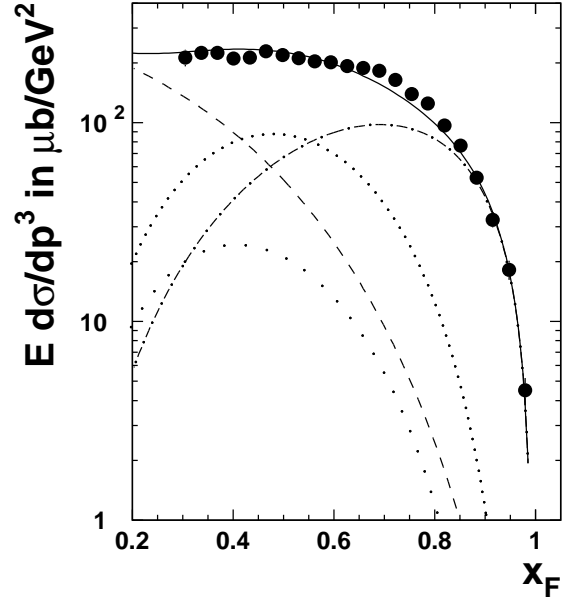


Figure 1:

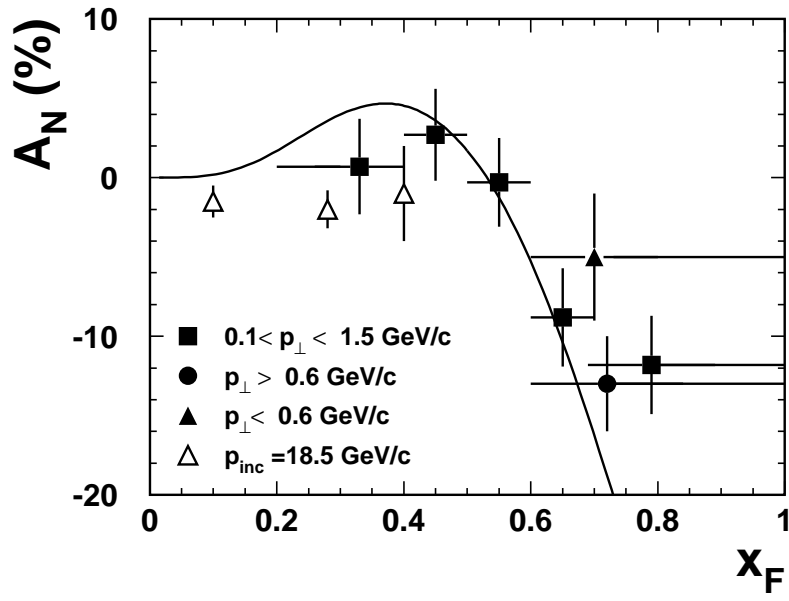


Figure 2:

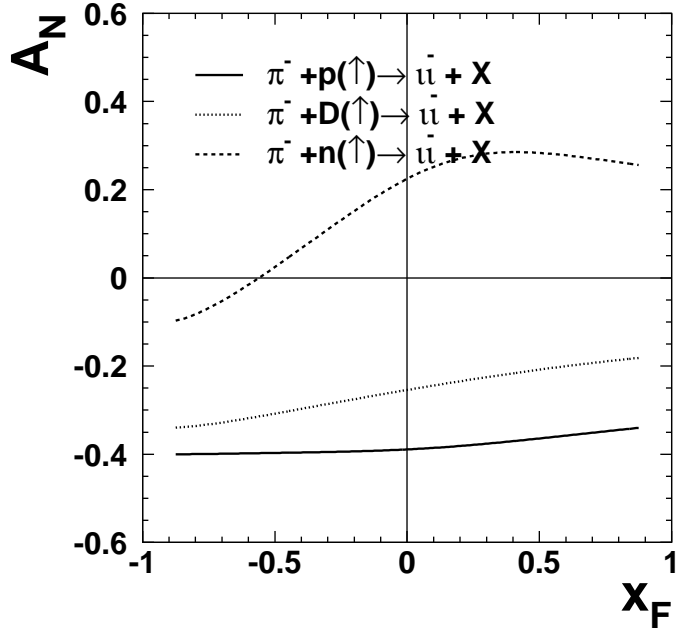


Figure 3:

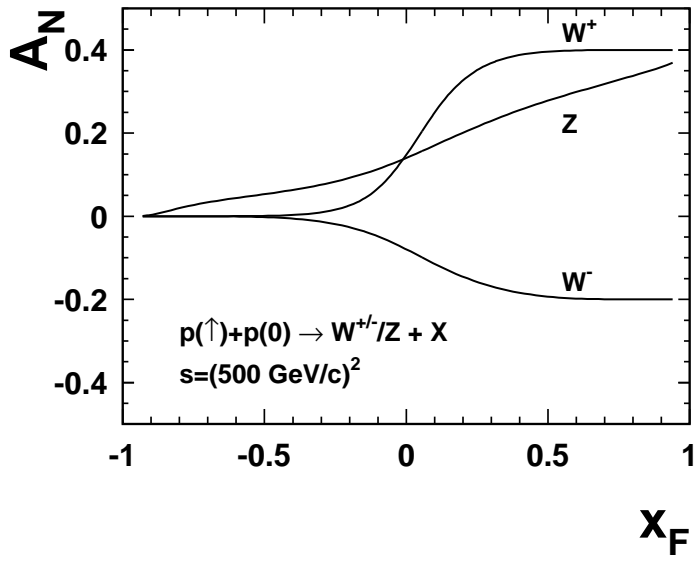


Figure 4: